Int J Life Cycle Assess (2011) 16:929–936
DOI 10.1007/s11367-011-0313-7

LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterisation to model the depletion of abiotic resources

Laura Schneider · Markus Berger · Matthias Finkbeiner

Received: 30 March 2011 / Accepted: 8 June 2011 / Published online: 19 June 2011

Abstract
Purpose Raw material availability is a cause of concern for many industrial sectors. When addressing resource consumption in life cycle assessment (LCA), current characterisation models for depletion of abiotic resources provide characterisation factors based on (surplus) energy, exergy, or extraction–reserve ratios. However, all indicators presently available share a shortcoming as they neglect the fact that large amounts of raw materials can be stored in material cycles within the technosphere. These "anthropogenic stocks" represent a significant source and can change the material availability significantly. With new characterisation factors, resource consumption in LCA will be assessed by taking into account anthropogenic material stocks in addition to the lithospheric stocks. With these characterisation factors, the scarcity of resources should be reflected more realistically.
Materials and methods This study introduces new characterisation factors—the anthropogenic stock extended abiotic depletion potentials—for the impact category depletion of abiotic resources. The underlying characterisation model is based on the conventional model but substitutes *ultimate reserves* by *resources* and adds anthropogenic material stocks to the lithospheric stocks.
Results and discussion A fictional life cycle inventory, consisting of 1 kg of several metals, was evaluated using different characterisation factors for depletion of abiotic resources. Within this analysis it is revealed that materials with relatively large anthropogenic stocks, e.g. *antimony* and *mercury*, contribute comparatively less to abiotic depletion when using the new characterisation factors. Within a normalized comparison of characterisation factors, the impact of anthropogenic stock results in relative differences between −45% and +65%, indicating that anthropogenic stocks are significant.
Conclusions With the new parameterisation of the model, depletion of abiotic resources can be assessed in a meaningful way, enabling a more realistic material availability analysis within life cycle impact assessment. However, a larger set of characterisation factors and further research are needed to verify the applicability of the concept within LCA practice.

Keywords Abiotic depletion potential · Anthropogenic stock · LCA · Material availability · MFA

1 Introduction

1.1 Background and objective

Humankind has consumed more minerals during the past century than in all earlier centuries together (Tilton 2003). The problem with the consumption of those resources is their decreasing availability for future generations (Brentrup et al. 2002). As raw materials are important for most industrial sectors, potential scarcity is a matter of concern for many stakeholders. In current life cycle impact assessment (LCIA) practice (ISO 14040 2006), resource use is evaluated by means of indicators based on (surplus) energy to mine this resource (Goedkoop and Spriensma 2001; PE International 2010), exergy of all resources required to provide a product (Bösch et al. 2007), or by means of the ratio of raw material extraction to lithospheric stock of this material, the abiotic depletion potential (ADP,

L. Schneider (✉) · M. Berger · M. Finkbeiner
Technische Universität Berlin,
Department of Environmental Technology,
Chair of Sustainable Engineering, Office Z1,
Straße des 17. Juni 135,
10623 Berlin, Germany
e-mail: laura.schneider@tu-berlin.de

Guinée et al. 2001). In a previous study (Berger and Finkbeiner 2011), significant correlations (R^2 up to 0.96) between those indicators have been revealed demonstrating that the results obtained in LCIA are rather independent from the impact category chosen. Thus, a closer assessment of one indicator appears to be sufficient for the consideration of resource use.

Gerst and Graedel (2008) pointed out that the continued increase in the use of metals over the twentieth century has led to the phenomenon of a substantial shift in metal stocks from the lithosphere to the anthroposphere. As this stock will become available in the future for recycling and reuse, the accumulated stocks in society have to be acknowledged when assessing the future resource availability or the depletion potential of a material. As resources are depleted only when they leave the economy in a form that functionality can no longer be restored (Stewart and Weidema 2005), these "anthropogenic stocks" represent a significant source and can change raw material availability significantly (Kapur and Graedel 2006; Brunner and Rechberger 2004). Yet, so far, all indicators neglect the fact that large amounts of raw materials are stored in material cycles within the technosphere. Thus the aim of the study is to introduce new characterisation factors, the anthropogenic stock extended abiotic depletion potentials (AADP), for the impact category depletion of abiotic resources. With the new characterisation factors, resource consumption in LCA is assessed by taking into account anthropogenic material stocks in addition to the lithospheric stocks. With this characterisation factor, the scarcity of resources should be reflected more realistically. To include the anthropogenic stock into the assessment of resource depletion, data from material flow analyses (MFA) can be used (Brunner and Rechberger 2004). The analysis of material flows is already an important part of every LCA. But here flows are always associated to one product and not related to the whole material cycle. As MFA provides important insights, an inclusion of aspects into the environmental assessment of products seems meaningful.

After determining a set of characterisation factors for relevant metals, the new method is applied and tested in a theoretical case study. The results are evaluated and compared to results obtained by means of the conventional ADP (Guinée 1995; Guinée et al. 2001; van Oers et al. 2002) underlining the relevance of this enhancement.

1.2 Definitions and data

In the following sections, relevant terms related to the calculation of the abiotic depletion potential are defined according to existing definitions (see also Fig. 1). The *ultimate reserves*, so far used to assess ADP in the default characterisation model, are defined as the amount of a resources that is ultimately available in the earth's crust (natural concentration of the resource multiplied by the mass of the crust) (van Oers et al. 2002; Guinée 1995). The definition of *ultimate reserves* comprises the total deposits of an element in the earth's crust without considering its actual concentration (Brentrup et al. 2002). *Reserves*, *reserve base*, and *resources* describe amounts of material with different anticipated time horizons concerning availability. Is the deposit rich enough to be mined at a profit today, it is termed (economic) *reserve*. Deposits that fulfil minimum physical and chemical criteria but are not economically extractable at the moment plus the *reserve* are termed *reserve base*. A *resource* describes the amount of mineral in such concentrated form that economic extraction is currently or potentially feasible (USGS 2010b; Kapur and Graedel 2006).

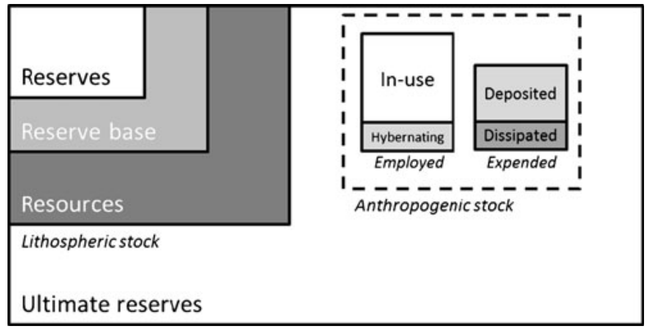

Fig. 1 Types of lithospheric and anthropogenic material stocks (based on Kapur and Graedel (2006)

When referring to the anthropogenic stock, metals can also exist in different conditions which give an indication about the actual availability of the material. *Employed stock* is the amount represented in the anthroposphere that is still in use and not yet discarded while *hibernating stock* represent the amount of resource that is not used anymore, but which has not been discarded yet, either. *Expended stock* is the total amount of resource that has been discarded. Thereby, the *deposited stock* is the amount of the resource that has been deposited, in, e.g. landfills, and the *dissipated stock* is the amount of a resource that has been returned to nature in a form that makes recovery almost impossible (Kapur and Graedel 2006). In Fig. 1 the interrelation between the different kinds of material stocks are displayed (not drawn to scale).

Until recently, the main focus of MFA was on flows. During past years however, it was realized that material stocks may be equally or sometimes even more important (e.g. Kleijn et al. 2000; Müller et al. 2006; Rauch 2009). By dynamically analysing the flow of materials, information about the stock in society can be obtained (see, i.a. Daigo et al. 2007; Hatayama et al. 2010, 2007). Yet, as MFA is time consuming and complicated to conduct, especially with a global focus, existing data are limited and uncertainties are not quantified.

Currently, data for anthropogenic stocks generated through MFA are available for a limited number of materials only (UNEP 2010). For this reason, anthropogenic stocks in this study were determined as the accumulated extraction rate since the beginning of records, in approximately 1900, until 2008 based on data from the U.S. Geological Survey (USGS 2010a). It is assumed that the amount of materials mined before is negligibly low in comparison to the large volumes and rates extracted since 1900. The material is present in the technosphere as either *in-use*, *hibernating*, *deposited*, or *dissipated anthropogenic stock*. Hence, the total mass of one metal in society, regardless of its chemical form, is included in the assessment of the anthropogenic stock (UNEP 2010). It should however be noted that the *dissipated stock*, which comprises the fraction of anthropogenic stocks that is lost due to, e.g. leaching or chemical reactions (Kapur and Graedel 2006), should actually be subtracted from the total anthropogenic stock in the calculation. As detailed material flow analysis of *copper* has shown that the *dissipated stock* accounts for less than 1% (Kapur and Graedel 2006), this is neglected in this study for the time being. However, it has to be acknowledged that materials have different characteristics that influence the amount of dissipation. For a more accurate analysis, a close assessment of individual materials has to be conducted in future studies.

2 Methodology

2.1 System description

In this section the development of the new parameterisation of the characterisation model is described more closely. The adaptation of existing characterisation factors will be conducted in two steps: The first step refers to an adjustment of the lithospheric stock considered for the assessment of material depletion (discussed below), and the second step is the inclusion of the anthropogenic stock into the characterisation model.

Within the current ADP model (Guinée et al. 2001), the total amount of a material in the earth's crust is used. However, these *ultimate reserves* are not a good indicator to measure resource scarcity as they will never actually be used for mining (Müller-Wenk 1998) and cannot reflect shortages. Any material will eventually deplete, even if lower and lower grade ores are included in the extraction, as costs and impacts will become too high (Steen 2006). When providing the conventional ADP characterisation model, Guinée (1995) already pointed out that rather the consideration of the *ultimately extractable reserve* would be the relevant parameter with regard to depletion.

Adjustments of the conventional model have been proposed before. Following the assumption of Brentrup et al. (2002), only *reserves* should be applied as *reserve base* or *resources* are dependent on further technical developments which are not considered within LCA. Guinée et al. (2001) and van Oers et al. (2002) already proposed to use the *economic reserves* instead of the *ultimate reserves* in an alternative characterisation model. Yet, these economic *reserves* and also the *reserve base* are actually not directly related to the depletion problem, as noted by Guinée (1995), but more an economic parameter, subject to constant change as directly dependent on the price of a material.

A valid, long-term assessment has to acknowledge the relevance of technical improvements as these are actually a main incentive to conduct LCAs and are important with regard to resource use. Moreover, for the inclusion of anthropogenic stocks into the assessment, consistency with lithospheric stocks regarding the availability time frame has to be considered. In this paper determination of the anthropogenic stock, as described in the introduction, is based on the theoretical extractable amount in society (disregarding the *dissipated stock*).

For the combination of lithospheric and anthropogenic stocks, it is important to merge consistent stocks which provide similar availability characteristics with regard to occurrence and concentration. Thus, and also as discussed by Guinée (1995) and van Oers et al. (2002), the determination of geological availability within this work should also be oriented on the extractable amount of a resource. However, these geological reserves are hard to detect, and hence an approximation has to be used. As the consistency of anthropogenic stocks and reserve figure used is of importance, geological reserves for this study are best described with *resources* (according to the U.S. Geological Survey (2010c)). *Resources* are by definition located between *reserve base* and *ultimate reserves*, and thus closest to the definition of *ultimately extractable reserves* (Guinée 1995; van Oers et al. 2002). Therefore it seems consistent to combine *resources* and the total anthropogenic stock as both describe deposits for which extraction is currently or potentially feasible and both depend on the technological and economic development in the future.

2.2 Characterisation model

In their default characterisation model, Guinée et al. (2001) determined the characterisation factors for depletion of abiotic resources.

$$\mathrm{ADP}_{i,\text{ ultimate reserves}} = \frac{\text{extraction rate } i}{(\text{ultimate reserves } i)^2} \times \frac{(\text{ultimate reserves antimony})^2}{\text{extraction rate antimony}} \tag{1}$$

As shown in Eq. 1, $\mathrm{ADP}_{i,\text{ ultimate reserves}}$ is calculated by first dividing the extraction rate of raw material *i* by the

square of the ultimate reserves of raw material i in total available on earth. Second, this ratio is put in relation to the extraction–ultimate reserve ratio of the reference resource *antimony*. The contribution to the depletion of abiotic resources of a product is calculated by multiplying each raw material input (m_i) into the product system under study by its corresponding characterisation factor, the abiotic depletion potential (ADP_i, see Eq. 2) (Guinée et al. 2001).

$$ADP = \Sigma ADP_i \times m_i \tag{2}$$

In order to determine the new characterisation factors AADP, the characterisation models proposed by Guinée et al. (2001) are modified in two steps. First, resources are used instead of ultimate or economic reserves (see Eq. 3).

$$ADP_{i,\text{ resources}} = \frac{\text{extraction rate } i}{(\text{resources } i)^2} \times \frac{(\text{resources antimony})^2}{\text{extraction rate antimony}} \tag{3}$$

Second, the anthropogenic stock of a raw material (as defined in previous sections) is added to the resource (see Eq. 4).

$$AADP_{i,\text{ resources}} = \frac{\text{extraction rate } i}{(\text{resources } i + \text{anthropogenic stock } i)^2} \times \frac{(\text{resources antimony} + \text{anthropogenic stock antimony})^2}{\text{extraction rate antimony}} \tag{4}$$

In this study all data for extraction rates, resources, and stocks were derived from the USGS (e.g. 2010b). For conventional ADP values according to the CML guideline (Guinée et al. 2001) are applied.

The impact assessment for the category depletion of abiotic resources was accomplished by applying the conventional ADP (Guinée et al. 2001), the same model, but replacing ultimate reserves with resources ($ADP_{resources}$) and the AADP. The characterisation factor $ADP_{resources}$ was added for identifying the actual influence anthropogenic stocks have on the results. Based on the characterisation models shown in Eqs. 3 and 4, characterisation factors for a range of relevant metals are calculated and the newly parameterised model is tested by evaluating a fictional life cycle inventory. For simplicity the fictional inventory contains the elementary input flows of 1 kg of each material.

3 Results and discussion

On the basis of the characterisation model described in the previous section, abiotic depletion potentials were calculated. For now, due to limited data access, the focus of this study is on ten materials only. Future work will encompass a larger set of materials focusing especially on scarce metals and potential relief through the inclusion of anthropogenic stocks into the assessment. Table 1 shows $ADP_{resources}$ and AADP characterisation factors derived from the conventional ADP characterisation model (Guinée et al. 2001).

The assumption that $ADP_{resources}$ and AADP factors should be larger than ADP factors because material availability decreases when *resources* and anthropogenic stocks are used instead of *ultimate reserves*, however, is not necessarily the case. As all factors express the result in relation to the reference resource *antimony*, the characterisation factors can hardly be compared directly. Only the ratio of, e.g. $ADP_{resources,\ Cu}$ to $ADP_{resource,\ Ni}$ can be compared to the ratio of $AADP_{Cu}$ and $AADP_{Ni}$. For the AADP, the difference between the ratios is dependent on the anthropogenic stock-

Table 1 Characterisation factors for material portfolio

Raw material	Extraction rate [t/a][a]	Resource [t][b]	Anthropogenic stock [t][c]	ADP [t Sb-e./kg][d]	$ADP_{resources}$ [t Sb-e./t]	AADP [t Sb-e./t]
Al	3.90E+07	7.50E+10	8.73E+08	1.00E-08	1.27E-06	5.34E-06
Cd	2.01E+04	6.00E+06	1.04E+06	3.30E-01	1.02E-01	3.19E-01
Co	7.59E+04	1.50E+07	1.94E+06	2.62E-05	6.18E-02	2.08E-01
Cu	1.57E+07	2.30E+09	5.11E+08	1.94E-03	5.44E-04	1.57E-03
Fe	2.22E+09	8.00E+11	5.71E+10	8.43E-08	6.36E-07	2.38E-06
Hg	1.32E+03	6.00E+05	5.46E+05	4.95E-01	6.72E-01	7.92E-01
Ni	1.57E+06	1.30E+08	4.78E+07	1.08E-04	1.70E-02	3.91E-02
Pb	3.80E+06	1.50E+09	2.17E+08	1.35E-02	3.10E-04	1.02E-03
Sb	1.65E+05	5.50E+06	5.90E+06	1.00E+00	1.00E+00	1.00E+00
Zn	1.16E+07	1.90E+09	4.18E+08	9.92E-04	5.89E-04	1.70E-03

[a] USGS (2010b)

[b] Butterman and Carlin (2004), Deutsches Kupferinstitut (2011), Frondel et al. (2006), Hill and Sehnke (2006), and USGS (2007, 2010b)

[c] USGS (2010a)

[d] According to Guinée (1995) and Guinée et al. (2001)

resource relation of the materials. Hence, materials with relatively large anthropogenic stocks will contribute comparatively less to abiotic depletion than materials with relatively low anthropogenic stocks (Berger et al. 2010).

This rather theoretical discussion is illustrated by means of the case study in which a fictional life cycle inventory, consisting of 1 kg of each metal, was evaluated using ADP, $ADP_{resources}$, and AADP. The results on the inventory level and for the impact category depletion of abiotic resources when using ADP, $ADP_{resources}$, or AADP characterisation factors are shown in Fig. 2.

In Fig. 2 only cadmium (Cd), mercury (Hg), and antimony (Sb) contribute to the impact assessment results in a noticeable manner while the remaining metals cause minor impacts only. Overall comparing the results of ADP, $ADP_{resources}$, and AADP, it appears that no big differences are obtained by means of the new parameterisation of the characterisation model. Even though, e.g. cobalt (Co), which is not significant for ADP, has a contribution to $ADP_{resources}$ and AADP, the result is also dominated by the impacts resulting from the abiotic depletion of antimony, mercury, and cadmium—with a similar percentage contribution. Considering the equally distributed inventory containing 1 kg of each metal, the relative values in Fig. 2 also reflect a direct comparison of the characterisation factors shown in Table 1. As characterisation factors for cadmium, mercury, and antimony are largest and similarly distributed in ADP and AADP, it is logical that they dominate the results and lead to similar findings. Hence, one should not generalize that no differences are obtained by means of the new characterisation factors. In a second analysis shown in Fig. 3, the dominating metals were excluded from the analysis and the results are again displayed using ADP, $ADP_{resources}$, and AADP characterisation models.

While ADP results in Fig. 3 are dominated by the abiotic depletion of lead (Pb), cobalt and nickel (Ni) contribute most to the $ADP_{resources}$ and AADP category indicator result, with slight differences. Hence, lead is regarded as the scarcest metal in the inventory when computing characterisation factors based on the ratio of extraction rate to ultimate reserves. In contrast, when calculating extraction–reserve ratios by means of the sum of *resources* or *resources* and anthropogenic stocks, lead is of less importance and cobalt is regarded as the most critical metal, followed by nickel. Obviously, criticality of certain materials is different with regard to the new characterisation factors, providing different implications for decisions. In Fig. 2 a visible difference between $ADP_{resources}$ and AADP can be found. For example antimony and mercury stocks are larger or almost as large as the *resources*. Thus the pressure displayed by the $ADP_{resources}$ should be higher than compared to the pressure displayed by AADP. By means of Fig. 2 this can be verified. Large stocks are thus reducing the pressure on a resource and have a comparably lower impact on the depletion of abiotic resources. The difference between $ADP_{resources}$ and AADP characterisation factors displayed in Fig. 3 seems to be small. Therefore, in Fig. 4, the difference of the characterisation models is displayed more closely to emphasize the significance of the new approach. Hereby all factors are normalized to copper (Cu) for an easier interpretation of results.

For materials with large anthropogenic stocks, the characterisation factor is decreasing because the denominator is increasing. By assessing the relative change compared to copper, e.g. $AADP_{Ni}$ to $AADP_{Cu}$, the large nickel stock will lead to a smaller ratio than the same comparison for $ADP_{resources}$. This confirms that the consideration of anthropogenic stocks leads to different impacts for materials within the characterisation models (here, materials with larger anthropogenic stocks than copper (mercury, antimony, and nickel) contribute comparably less to abiotic depletion). Positive bars in Fig. 4 represent values beneath 100% for AADP/ADPresources, standing for a

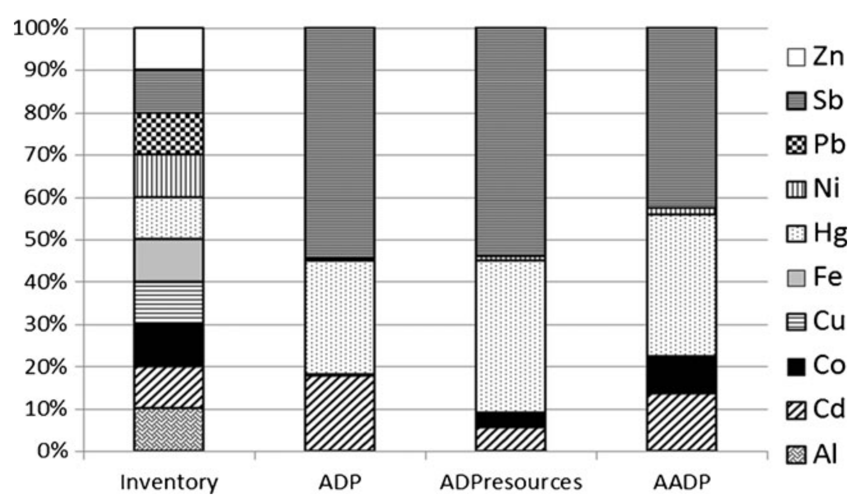

Fig. 2 Contribution of metals to the impact category depletion of abiotic resources

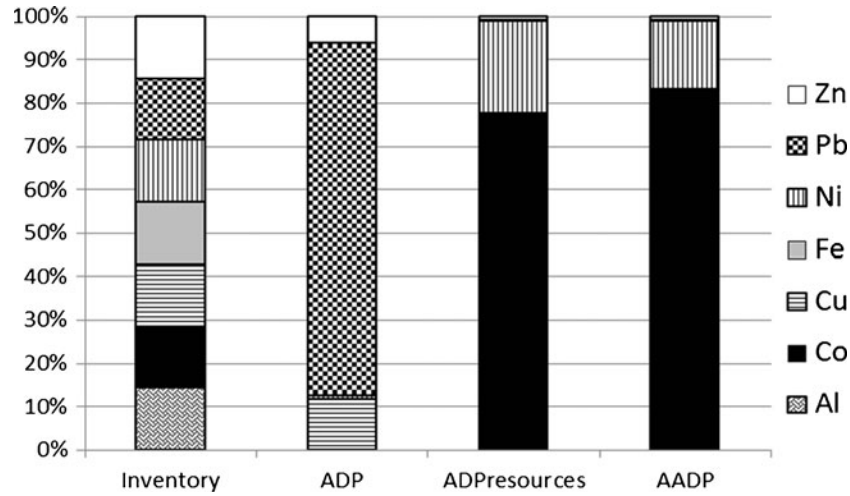

Fig. 3 Contribution of selected metals to the impact category depletion of abiotic resources

comparably lower depletion potential compared to copper when applying AADP, and vice versa. Given that in Fig. 3 the contribution is displayed as a function of the sum of all characterisation factors, these differences are not as obvious. With growing anthropogenic stocks and increasing data availability, the AADP characterisation factors will become more important for a realistic assessment of resource depletion. It is revealed that the impact of anthropogenic stock results in relative differences between −45% and +65%, indicating that anthropogenic stocks are significant.

As stated within the definition of the conventional ADP characterisation factor (Guinée 1995), reserves of a material are taken into account more than once (by putting a square to the denominator (see Eq. 1)) to provide a realistic depiction of resource criticality (when assessing the effect of 1 kg of extraction). Underlying is the fact that small stocks are a more important indicator for resources depletion than large extraction rates. Simply comparing extraction rates and stocks would lead to different results. This implies that the stocks of materials have a comparably higher importance than extraction rates within the calculation of characterisation factors (Guinée 1995). Thus, the difference between the extraction rates used for conventional ADP and for $ADP_{resources}$/AADP (USGS 2010b) should not be a determining factor. It seems that the AADP characterisation model can enable a more realistic assessment of depletion of abiotic resources with regard to, e.g. the implementation of new technologies.

However, there are still challenges which currently remain unsolved. The lack of data concerning *resources* and anthropogenic stocks inhibits the calculation of a larger set of characterisation factors. Furthermore, from a methodological point of view, it is still unclear how anthropogenic stocks can be calculated for, e.g. fossil fuels, for which plastics available in the technosphere might serve as anthropogenic deposit to a certain degree.

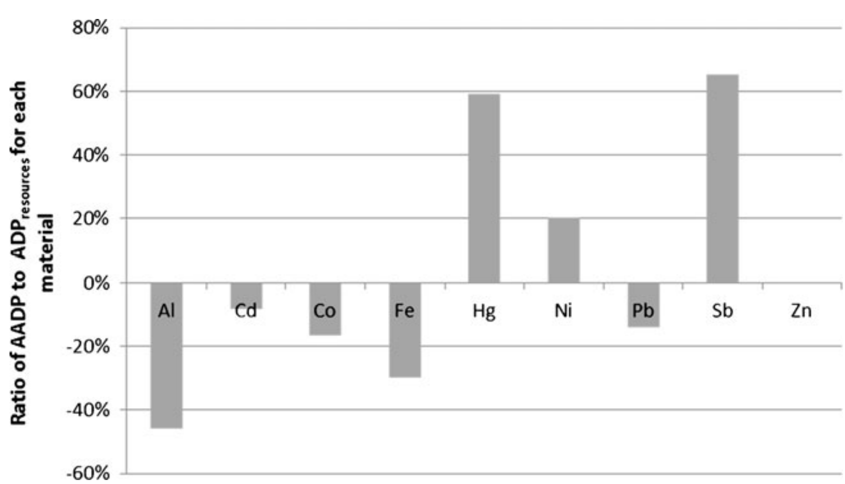

Fig. 4 Characterisation factors $ADP_{resources}$ compared to AADP (normalized to copper)

4 Conclusions and outlook

In order to allow for a more realistic material availability assessment, a new parameterisation of the characterisation model for depletion of abiotic resources was introduced. A case study in which a fictional life cycle inventory was assessed using ADP, $ADP_{resources}$, and AADP characterization models revealed different results. Metals like cobalt and nickel, which are perceived as critical for future technologies (e.g. Angerer et al. 2009), do not influence the ADP result at all. As these metals contribute more to the AADP category indicator result, the new parameterisation seems to enable a more realistic assessment of resource use in LCA. The differences assessed between $ADP_{resources}$ and AADP underline the relevance of anthropogenic stocks for the assessment of abiotic depletion. However, a larger set of characterisation factors and further research are needed to verify the applicability of the concept within LCA practice.

There are some challenges associated with this new parameterisation and the inclusion of the anthropogenic stock into the calculation of abiotic depletion potentials. The classification of the anthropogenic stock is complicated and requires thorough analysis as it occurs in many different states within the anthroposphere. This makes an exact quantification difficult as measurement of the recoverable part of anthropogenic stocks is complicated. Besides, the quality of recovered materials might not be sufficient for certain applications, or large amounts of the material are subject to degradation in the atmosphere (Graedel and McGill 1986). Such restrictions need to be addressed in future studies and have to be determined for every material individually (Stewart and Weidema 2005). Furthermore, each material is unique and the depletion of natural minerals represents different environmental problems (van Oers et al. 2002; Brentrup et al. 2002). The inclusion of anthropogenic stock is considered to have a positive effect within this study. However, in reality, anthropogenic stocks can also induce environmental pressure, e.g. due to material dissipation from *in-use stocks*. Thus, larger stocks could also have negative effects on the environment. For future advancements anthropogenic stocks should be considered extensively within life cycle assessment. In addition to the "geological assessment" of resource availability, ongoing work also encompasses the evaluation of economic material availability within life cycle sustainability assessment (Schneider et al. 2011).

The future resource assessment has to be advanced to meaningfully consider more aspects associated with the extraction and use of resource. The developed characterisation factors still lack significance due to data uncertainties, especially on the global level. However, with improving inputs by means of MFA, the characterisation factors will gain increasing importance for the assessment of depletion of abiotic resources within LCA. A comprehensive approach by enhancing LCA with MFA data is important for future decision making.

References

Angerer G, Erdmann L, Marscheider-Weidemann F, Scharp M, Lüllmann A, Handke V, Marwede M (2009) Rohstoffe für Zukunftstechnologien. Fraunhofer IRB Verlag, Stuttgart

Berger M, Finkbeiner M (2011) Correlation analysis of life cycle impact assessment indicators measuring resource use. Int J Life Cycle Assess 16:75–81

Berger M, Schneider L, Finkbeiner M (2010) A new characterization model for depletion of abiotic resources—the antrhopogenic stock extended abiotic depletion potential. In: The 9th International Conference on EcoBalance, Tokyo, 9–12 November 2010

Bösch ME, Hellweg S, Huijbregts MAJ, Frischknecht R (2007) Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. Int J Life Cycle Assess 12:181–190

Brentrup F, Küsters J, Lammel J, Kuhlmann H (2002) Impact assessment of abiotic resource consumption. Int J Life Cycle Asses 7(5):301–307

Brunner PH, Rechberger H (2004) Practical handbook of material flow analysis. Lewis Publishers, Boca Raton

Butterman WC, Carlin JF (2004) Antimony. Mineral commodity profiles. U.S. Geological Survey

Daigo I, Igarashi Y, Matsuno Y, Adachi Y (2007) Accounting for steel stock in Japan. ISIJ Int 47(7):1065–1069

Deutsches Kupferinstitut (2011) Vorkommen und Gewinnung. http://www.kupfer-institut.de/front_frame/frameset.php3?client=1&lang=1&idcat=34&parent=14. Accessed 22 Feb 2011

Frondel M, Angerer G, Buchholz P, Grösche P, Huchtemann D, Oberheitman A, Peters J, Vance C, Sartorius C, Röhling S, Wagner M (2006) Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen. Rheinisch-Westfälisches Institut für Wirtschaftsforschung, Fraunhofer-Institut für System- und Innovationsforschung, Bundesanstalt für Geowissenschaften und Rohstoffe

Gerst MD, Graedel TE (2008) In-use stocks of metals: status and implications. Environ Sci Technol 42(19):7038–7045

Goedkoop M, Spriensma R (2001) The Eco-indicator 99—a damage oriented method for life cycle impact assessment. Product Ecology Consultants (PRe), Amersfoort

Graedel TE, McGill R (1986) Degradation of materials in the atmosphere. Environ Sci Technol 20(11):1093–1100

Guinée JB (1995) Development of a methodology for the environmental life-cycle assessment of products; with a case study on margarines. Leiden University

Guinée JB, de Bruijn H, van Duin R, Gorree M, Heijungs R, Huijbregts MAJ, Huppes G, Kleijn R, de Koning A, van Oers L, Sleeswijk AW, Suh S, de Haes HA Udo (2001) Life cycle assessment—an operational guide to the ISO standards, part 2b. Centre of Environmental Science—Leiden University (CML), Leiden

Hatayama H, Yamada H, Daigo I, Matsuno Y, Adachi Y (2007) Dynamic substance flow analysis of aluminium and its alloying elements. Mater Trans 48(9):2518–2524

Hatayama H, Daigo I, Matsuno Y, Adachi Y (2010) Outlook of the world steel cycle based on the stock and flow dynamics. Environ Sci Technol 44(16):6457–6463

Hill VG, Sehnke ED (2006) Bauxite. In: Kogel JE, Trivedi NC, Barker JM, Krukowski ST (eds) Industrial minerals and rocks. SME, Littleton

ISO 14040 (2006) Environmental management—life cycle assessment—principles and framework (ISO 14040:2006). European Committee for Standardisation, Brussels

Kapur A, Graedel TE (2006) Copper mines above and below the ground. Environ Sci Technol 40(10):3135–3141

Kleijn R, Huele R, Evd V (2000) Dynamic substance flow analysis: the delaying mechanism of stocks, with the case of PVC in Sweden. Ecol Econ 32:241–254

Müller DB, Wang T, Duval B, Graedel TE (2006) Exploring the engine of anthropogenic iron cycles. PNAS 103(44):16111–16116

Müller-Wenk R (1998) Depletion of abiotic resources weighted on base of “virtual” impacts of lower grade deposits used in future. Institut für Wirtschaft und Ökologie, St. Gallen

PE International (2010) http://www.gabi-software.com. Accessed 20 Dec 2010

Rauch JN (2009) Global mapping of Al, Cu, Fe, and Zn in-use stocks and in-ground resources. PNAS 106(45):18920–18925

Schneider L, Berger M, Finkbeiner M (2011) Economic material availability as a new area of protection for life cycle sustainability assessment. In: SETAC Europe 2011, Milano

Steen BA (2006) Abiotic resource depletion. Int J Life Cycle Assess 11(Special Issue 1):49–54

Stewart M, Weidema B (2005) A consistent framework for assessing the impacts from resource use. Int J Life Cycle Assess 10 (4):240–247

Tilton JE (2003) On borrowed time? Assessing the threat of mineral depletion. Resources for the Future, Washington

UNEP (2010) Metal stocks in society—scientific synthesis. International Panel for Sustainable Resource Management

USGS (2007) Cadmium. Mineral commodity summaries. U.S. Geological Survey

USGS (2010a) Historical statistics for mineral and material commodities in the United States. U.S. Geological Survey, Washington

USGS (2010b) Mineral commodity summaries. U.S. Geological Survey, Washington

USGS (2010c) Mineral commodity summaries. Appendix C. U.S. Geological Survey, Washington

van Oers L, deKoning A, Guniée JB, Huppes G (2002) Abiotic resource depletion in LCA. Road and Hydraulic Engineering Institute